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QUARTERLY PROGRESS REPORT on CONTRACT NAS 8-2604 for the MEASUREMENTS AND IMPROVEMENTS OF TWO HYDROGEN MASERS

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INTRODUCTION

The period covered by this report is September 1, 1963 to November 30, 1963, and it will describe the work done in modifying the two NASA Atomic Hydrogen Masers and the data subsequently taken.

TECHNICAL REPORT

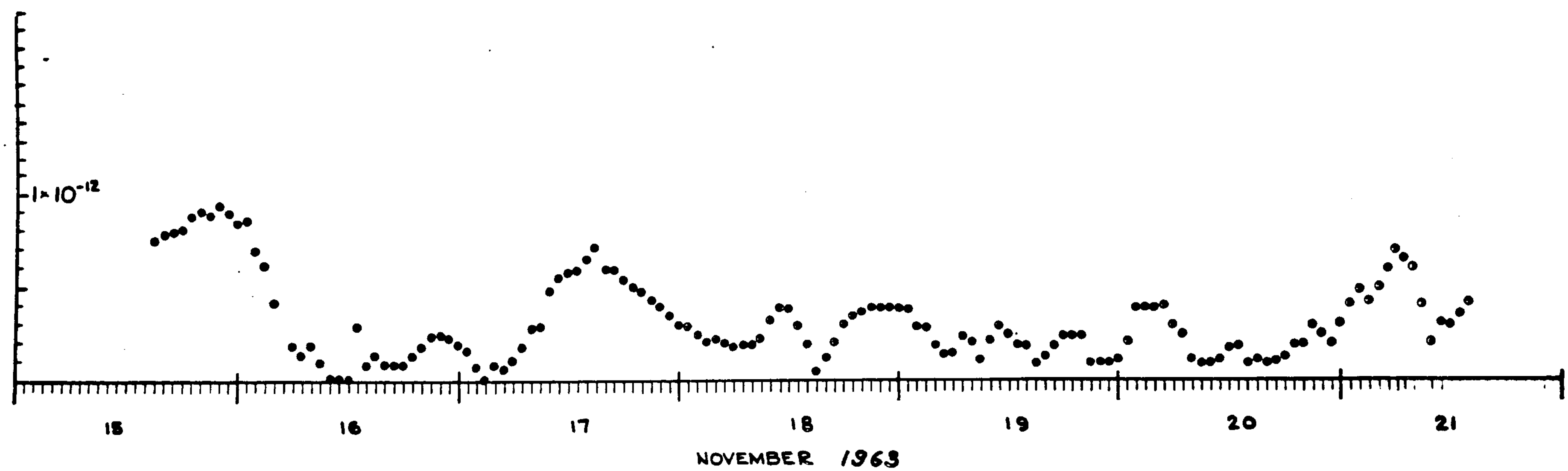
Task A - Conduct a measurement program for long and short term stability using three hydrogen masers.

Data so far has been taken between two masers located within the same lab environment. A set of measurements has been taken against a third device located about 50 feet away in a different room. The third device has been constructed somewhat differently from the other two in that the thermal compensation of the cavity has been improved as well as its thermal enclosure. Temperature control can be maintained to about $\pm 0.01^{\circ}C$ at the inner oven and the cavity is better isolated within the isothermal enclosure making the effect of temperature gradients less important. The NASA devices using chopper-stabilized controllers have maintained about $\pm 0.02^{\circ}C$ and are sensitive to the level of the r.f. leakage from the dissociator discharge. Beat measurements between these two dissimilar devices have shown that variations in beat frequency correlated directly with the bell jar of the No. 1 NASA maser. Larger temperature excursions were imposed on this bell jar and the effect was greater. Since both the devices under investigation for NASA were built as identical to each other as possible, there is very little doubt that the thermal responses were correlated.

In an effort to reduct the thermal problems, the temperature of the room housing the masers was controlled to $\pm 2^{0}F$. A run was made of the frequency excursions and is shown in Figure 1.

Control of the cavity resonance frequency is vital for good short term stability and the solution to this problem can be obtained in two ways, by better thermal compensation and by better temperature control.

FREQUENCY-DIFFERENCE-BETWEEN
TWO
HYDROGEN MASERS



It is of interest to review the expected thermal properties of the solid dielectric cavity that is now under construction. The resonant frequency for a solid sphere is given by

$$\nu_c = \frac{4.50}{2\pi\sqrt{\mu\epsilon}}$$

a is spherical radius

$\sqrt{\mu\epsilon} = \frac{\sqrt{k_e k_m}}{C}$

k_e is dielectric constant

k_m is permeability $= 1$

C is velocity of light in vacuum

$$\frac{\partial\nu_c}{\nu_c} = -\frac{\partial a}{a}$$

and this will be taken for the cavity having a concentric dielectric discontinuity

$$\frac{\partial\nu_c}{\nu_c} = -\frac{\partial a}{\partial T}\,\partial T$$

For fused silica (Corning 7940) $\frac{\partial a}{\partial T} = 5.6 \times 10^{-7} a$

$$\frac{\partial\nu_c}{\nu_c} = -5.6 \times 10^{-7}\,\partial T$$

or $\partial\nu = 8$ cps for $\partial T = 10^{-2}\,^{\circ}C$.

The effect of cavity pulling is given by

$$\Delta\nu = \frac{Q_c}{Q_\ell}\,\Delta\nu_T$$

The cavity Q expected from this new cavity is about 10^4. Previously, the cavities have had Q's of 5 to 6×10^4. Lowering the cavity Q requires a larger threshold flux for oscillation or a shorter storage constant as seen in the equation given below.

$$I_{th} = \frac{hV\gamma^2}{8\pi^2\mu_o^2 Q\eta}$$

where

h is Planck's constant

V is the cavity volume

γ is the storage constant

μ_o is the Bohr magneton

η is the ratio of the square of the r.f. magnetic field in the storage volume to that in the whole cavity.

The parameter η will be readily calculable as the fields in the spherical cavity can be analyzed exactly. Formerly the problem of the dielectric loading of a spherical quartz bulb in a cylindrical cavity led to difficulties in calculating the fields.

The total pulling for a 10^{-2} ^{0}C change in temperature, assuming a line Q of 10^9, is 5×10^{-13}.

Task A is now complete.

Task B - Conduct measurements to determine the precision to which a given pair of masers can be reset with respect to frequency.

The modifications described in the report for the interval June 1, 1963 to August 31, 1963 have enabled us to measure the resettability and the validity of the technique of tuning via the spin exchange line Q modulation. During this period work by P. L. Bender[1] indicated that a shift in frequency will occur due to spin exchange collisions. Later calculations made by Stuart B. Crampton[2] et al. showed that this effect occurred with the same functional relationship as the cavity pulling and, in fact, by tuning the maser using the beam modulation technique the cavity is automatically set so as to pull the oscillation frequency back to the unperturbed maser frequency. The reason for this cancellation is that the shift in frequency is propostional to the line broadening as shown in the attached copy of an article submitted to Physical Review Letters.

The resettability has been found to be accurate to 2.1 parts in 10^{13} using this technique. Fundamental limitations of this method are due to noise in the receiver. A further, practical limitation has existed in the reproducibility of the tuner setting. This is easily overcome by using a finer tuning rate.

Task B is complete. Further measurements will be made when opportunities occur to make them; however, no significant changes are expected until the noise problem is overcome.

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1 Private communication, later published in Phys.Rev. 132, 2154 (Dec. 1963).

2 Phys.Rev. Letters 11 (October 1963).

Task C, that of making short term measurements, is now underway and the advantages of the Electron Beam Parametric Amplifiers, on loan from NASA, will undoubtedly improve the data obtained in Task B. However, this improvement is not likely to exceed a factor of five.

Task C - Conduct measurements to determine very short term relative stability. Very short term is defined as 0.01 seconds or less: approximately 3 months to complete after the approval of Task B.

The equipment for these measurements has been ordered from various electronic equipment suppliers. The system to be tried first is a balanced double hetrodyned system employing a common pump oscillator for the electron beam parametric amplifiers, a common local oscillator for the mixer, and a common 30 mc/sec. second hetrodyne to bring the spectrum to low frequency. The two low frequency outputs will be compared in phase by various techniques. The first will be a cross-correlation method employing an analog multiplier and integrator.

Task D - Measure the ratio of cesium to hydrogen frequencies of hyperfine separation; approximately 2 months to complete after approval of Task C.

Task D has already been discussed in a previous quarterly report. It is complete, having been accomplished in a manner different and better than anticipated. Further measurements of this will be made from time to time. It is not likely that any significant difference in precision will result as the Cesium frequency as given in the A.1 time scale is not reproducible to better than 1 in 10^{11}.

Task E - Compare the two NASA masers with those at Harvard, approximately one month to complete after approval of Task D.

There are two methods by which this can be accomplished. Originally, the method proposed was in physically transporting the masers to the Lyman Labs at Harvard and doing the comparison there. A further method has come to light due to the Loran "C" technique and concurrent measurements via Loran are planned with Harvard and possibly the USASRDL at Ft. Monmouth, N.J. These comparisons will show the reproducibility of the frequency from masers of very dissimilar origins.

STATUS OF IMPROVEMENTS TO THE MASERS

1. Solid Dielectric Cavity

The blanks have been obtained and have been sent to Engelhard for grinding. These should be ready early in January 1964.

2. Solid State R.F. Power Supply for the Discharge Tube

A crystal controlled supply has been built and delivers eight watts at 97 mc/sec; this design will be optimized to deliver about ten watts. A single stage uncontrolled oscillator at about 100 mc/sec is under construction and should deliver ten watts. This last unit could be mounted within the recess at the discharge tube and directly excite the Hydrogen discharge without a coupling cable. Excellent r.f. shielding is obtainable with their design.

3. Thermal Control

The stability of d.c. stabilized circuits using balanced matched transistors has been demonstrated as feasible and these circuits will be used in place of the three chopper stabilized equipments now in use to control inner, outer oven and neck gradients. Parts have been obtained and the circuit assembly has begun. The resistance heater windings will have to be changed and it is suggested that certain aspects of the design affecting the cavity compensation and thermal isolation within the bell jar also be modified.

TUNING OF THE HYDROGEN MASER*

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The cavity of the hydrogen maser[1] is tuned by measuring the output frequency of the maser against the hydrogen pressure. The expression, generally quoted in the literature, relating the output frequency, the cavity tuning and the atomic resonance line width $\Delta\nu_\ell$, is

$$(\nu - \nu_H) = \frac{Q}{\nu_H} \quad (\nu_c - \nu_H) \; \Delta\nu_\ell. \tag{1}$$

where ν is the observed frequency, ν_H the atomic resonance frequency, ν_c the cavity resonance frequency and Q the quality factor of the cavity. The atomic resonance line width is pressure dependent through the exchange collision relaxation process and the maser is assumed to be tuned if the output frequency stays constant as the hydrogen pressure is varied.

Bender[2], however, has calculated that exchange collisions in an atomic hydrogen gas cause a small frequency shift of the order of one fifth of the exchange line width. Crampton, Kleppner and Ramsey[3] pointed out that the effect disappears in an oscillating maser owing to the fact that the exchange collisions frequency shift "depends upon the atomic resonance width in the same fashion as the cavity pulling". When the pressure shift is taken into account, expression 1 is written,

$$(\nu - \nu_H) = \left[\frac{\nu_c - \nu_H}{\nu_c} \; Q - 0.29 \; \frac{\bar{v} \, a_o^2 \, \hbar}{Q \, \mu_o^2 \, \eta} \; \frac{V_c}{V_b} \right] \Delta\nu_\ell \tag{2}$$

where $\bar{v}$ is the mean velocity of the atoms in the maser storage bulb, a_o is the radius of the first Bohr orbit, $\hbar$ is Planck's constant over 2π, μ_o the Bohr magneton, V_c is the volume of the cavity, V_b is the volume of the storage bulb and η is the ratio of the average energy density in the bulb to the average energy density in the cavity. When the resonance frequency of the cavity is

$$\nu_c = \nu_H + 0.29 \frac{\nu_c \bar{v} a_o^2 \hbar}{Q^2 \mu_o^2 \eta} \frac{V_c}{V_b} \tag{3}$$

the output frequency is independent of the hydrogen pressure and is equal to ν_H.

A careful experiment has been done to verify these effects.[1] Two masers described in a previous paper (Vessot and Peters[4]) were used in the experiment. One of them was used as a comparison standard and operated at a magnetic field slightly higher than the other. The two masers were allowed to beat together and the time for ten beats was counted and recorded using a digital analog device. A typical period for 10 beats was 5.060 seconds of which the last two digits were recorded. The standard deviation for each maser over 5 second counting periods was 2.5 parts in 10^{13} evaluated from 165 measurements.

The experiment was done by varying the hydrogen pressure at various cavity frequency settings. Hydrogen beam flux was controlled by varying the temperature of the palladium purifier. The beam source pressure, measured with a Pirani gauge, and the period for ten beats were recorded simultaneously. The results are shown on Figure 4 for four different source pressures.

(Figure 1) (Figure 2)

This data was analysed by the method of least squares giving the equation of the four straight lines and it was found that the spread at the crossing of the various pressure curves did not exceed 0.0003 c.p.s. or 2.1 parts in 10^{13}. It is concluded that even considering the presence of pressure shifts, the hydrogen maser can be tuned with the technique previously used and described above. When the values of constants for a typical maser are used in expression (3) it is found that the maser should be tuned with the cavity resonance frequency set approximately 80 c.p.s. higher than the maser output; a measurement of the cavity resonance frequency would thus provide a verification of equation (3). Techniques are presently being sought to permit the absolute determination of the cavity resonance frequency to a sufficiently high accuracy for this measurement.

Two masers were tuned by the method described above. Their frequency difference, after tuning, was 7.6 parts in 10^{13}. It is believed that the resetability of the tuner of one of the masers was the limitation in this experiment.

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* This work is supported by the National Aeronautics and Space Administration under contract number NAS 8-2604.

[1] Daniel Kleppner, H. Mark Goldenberg and Norman F. Ramsey, Phys. Rev., 126, 603, 1962.

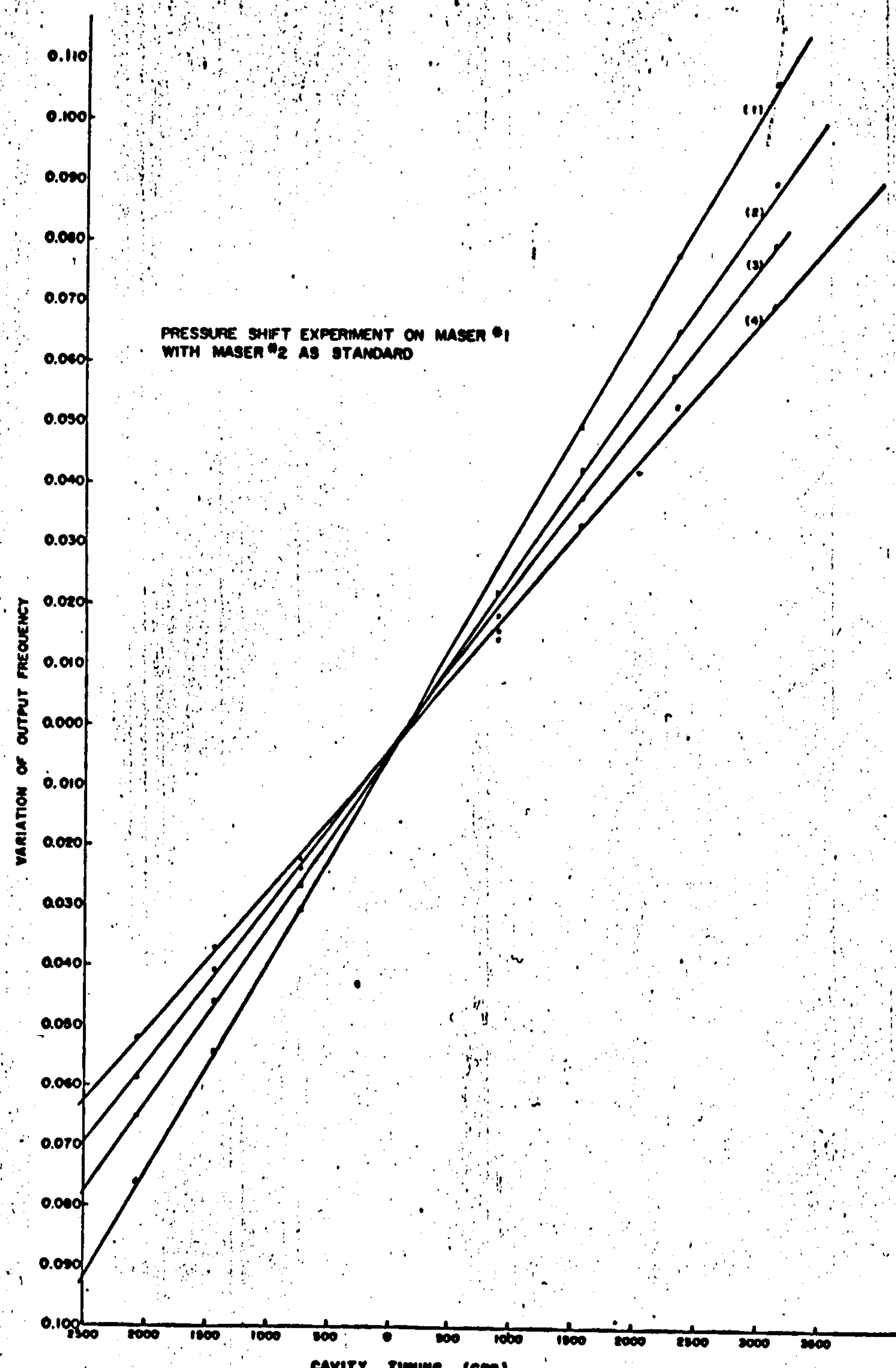
[2] P. L. Bender, Phys. Rev. (to be published)

[3] Stuart B. Crampton, Daniel Kleppner and Norman F. Ramsey, Phys. Rev. Let. Vol. 11, No. 7, p. 338.

[4] R. F. C. Vessot and H. E. Peters, I.R.E. Trans. on Inst. Vol. I-II #3 and 4, 183, 1962.

Figure 1 Variation of the output frequency of the maser against the cavity tuning. The curves are numbered 1, 2, 3, 4 corresponding to beam source pressures of 0.075, 0.044, 0.03 and 0.02 mm of Hg. respectively.

Figure 2 Block diagram of the apparatus used for tuning hydrogen masers.


PRESSURE SHIFT EXPERIMENT ON MASER #1
WITH MASER #2 AS STANDARD
VARIATION OF OUTPUT FREQUENCY
CAVITY TUNING (CPS)
(1)
(2)
(3)
(4)
0.110
0.100
0.090
0.080
0.070
0.060
0.050
0.040
0.030
0.020
0.010
0.000
0.010
0.020
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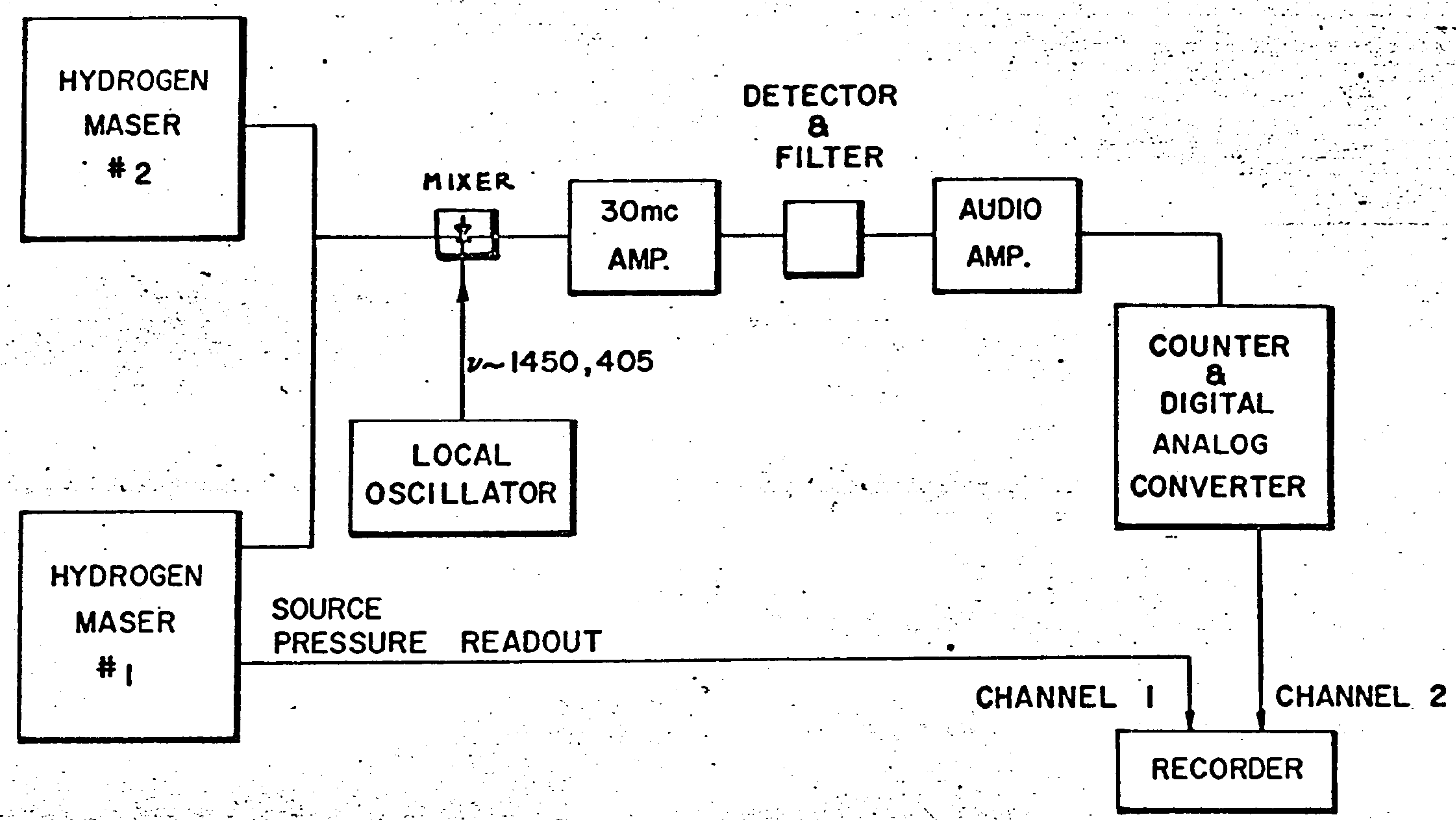

Figure 2 - Vanier and Vessot.